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Barriers to the Surface Transport of Oil

Chemistry and Physics Laboratory
The Ivan A. Getting Laboratories
The Aerospace Corporation
El Segundo, Calif. 90245

18 February 1977

Interim Report

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FOR THE COMMANDER

Arturo G. Fernandez
2nd Lt., U.S. Air Force
Technology Plans Division
Deputy for Advanced Space Programs

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The surface transport of oil in the presence of geometrical and chemical barriers has been investigated. The surface transport was induced by capillary forces, surface tension gradients, and gravity. It was learned that smooth edges of sufficient sharpness are as effective as anticreep agents in preventing oil migration. Rough surfaces, however, destroy this effect.

During this study, it was discovered that a chromatographic effect occurs when Apiezon C undergoes capillary flow on steel substrates. In this

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19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

process, some components of the oil travel faster than others, and a change in composition occurs as the oil front advances.

CONTENTS

FIGURES

I. INTRODUCTION

Liquid lubricants are used in most spacecraft moving mechanical assemblies (MMA) in the form of thin oil films 2 to 5 μm in thickness. For extended missions (>5 years), oil reservoirs (impregnated porous materials) are inserted into the MMA bearing annulus to facilitate the replenishment of lubricant lost by evaporation. In order to sustain acceptable performance throughout the operational lifetime of the MMA, it is desirable to maintain film thickness levels and oil distribution such that flooding or lubricant starvation cannot occur within a bearing cavity. Limited information exists, however, on the vapor transport and surface migration characteristics of lubricant oils impregnated into retainers and reservoirs or residing on the internal surfaces of an MMA bearing cavity. This lack of lubricant transfer data makes it impossible to model a priori the lubricant distribution within an MMA as a function of time and operating parameters.

This is one in a series of reports in which experiments dealing with these questions are being described. In earlier reports (1-6), the effect of a temperature gradient on a thin oil film was demonstrated, and the efficacy of porous lubricant reservoirs was investigated. In this report, some of the conditions under which oil migration is blocked by geometrical and chemical barriers are discussed.

II. EXPERIMENTAL TECHNIQUE

A. APPARATUS

The experimental apparatus was the same as that used in earlier studies on oil migration. The basic technique was to qualitatively determine the distribution of oil on a metal surface by photography of its fluorescence under ultraviolet light. A complete description of this method has been given in earlier reports (3, 5). The studies presented here were mostly carried out under ambient pressure.

B. SAMPLE PREPARATION

As in earlier studies, the oil migration was observed on $5 \times 2 \times 0.159$ cm metal substrates. Unless otherwise specified, the latter were machined from 347 stainless steel. For the geometrical barrier studies, the substrates carried steps, corners, and curves, which were machined into the upper surface when the substrates were made. The surface finish was either rough or smooth; the former was sandblasted and the latter finely machined to a finish of approximately 16-32 rms.

The cleaning procedure was the same as described earlier (5):

1. Ultrasonically clean in xylene
2. Spray rinse with freon
3. Soak in hot (80-90 C) Oakite HD 126 for 30 min
4. Rinse with H_2O
5. Rinse with distilled H_2O
6. Rinse with pure ethyl alcohol
7. Blow dry with nitrogen.

The oil films were prepared on the substrates by either dip coating or swabbing. In the dip coating process, the sample was suspended vertically in a 40 vol% solution of Apiezon C in heptane. The solution was then allowed to run out through a capillary in the bottom of the container such that a thin oil film (~3 μm) remained on the substrate (5). In the swabbing process, a cotton swab that had been dipped in a 40 vol% solution of Apiezon C in heptane was wiped over the substrate. For the geometrical barrier studies, the swabbing method was primarily used because the barrier interferred with the formation of a uniform film by the dip coating process.

After coating, unwanted oil was removed from the back and ends of the substrate with a heptane-soaked cotton swab. Nybar F, an anticreep agent, was then applied around the oil film in order to contain the oil and prevent its contamination by other sources.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. GEOMETRICAL BARRIERS

1. SMOOTH SURFACE FINISH

a. Thermally Driven Migration, Thin Films

Oil migration on a finely finished substrate in the presence of a typical geometrical barrier is shown in Fig. 1. The initial oil film was swabbed on, and its migration toward the right was induced by the application of a temperature gradient. A gradient of 1.7 C/cm was used first and later increased to 5.0 C/cm. The barrier prevented the oil on the left half of the substrate (Fig. 1) from migrating to the right half. This oil accumulated in the corner at the base of the barrier. Most of the oil on the right half of the substrate migrated normally to the end of the plate, i.e., up to the anticreep coating, except for a small quantity that was held at the base of the barrier.

The resultant oil distribution when this experiment was run on substrates with different types of barriers is shown in Fig. 2. The oil is indicated by the dark bands, and its thickness is greatly exaggerated. The results were the same when the samples were run in air or under vacuum. Also, geometries e and f were run with dip-coated substrates, again with the same results. The six geometries studied, therefore, acted as effective barriers to thermally induced oil migration.

In analyzing these results, we first note that, in some cases, gravity had to be overcome for the oil to pass the barrier (geometry b), but in others, gravity favored the flow of oil (geometry a). Gravity, therefore, is not responsible for the efficacy of the barriers. Rather, the barriers appear to work by means of two related effects whereby the oil is trapped in corners on the one hand and repelled from edges on the other. Both of these effects can be explained by capillary processes that involve the surface tension of the oil.

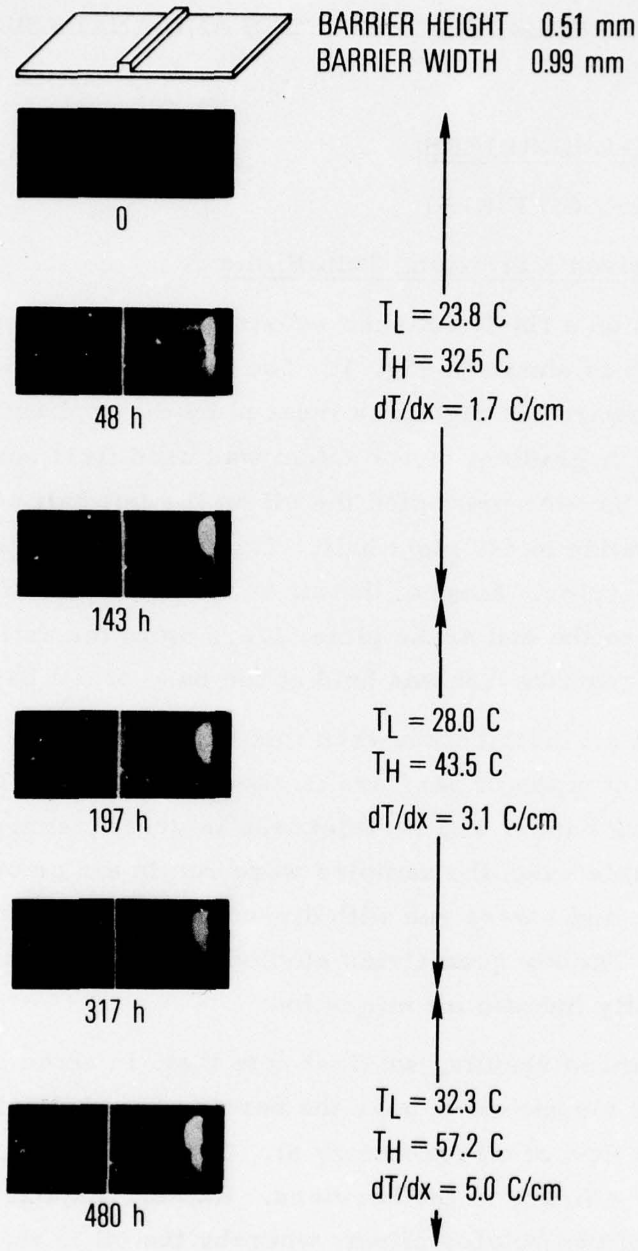


Figure 1. Thermally Induced Oil Migration in the Presence of a Geometrical Barrier (smooth surface finish)

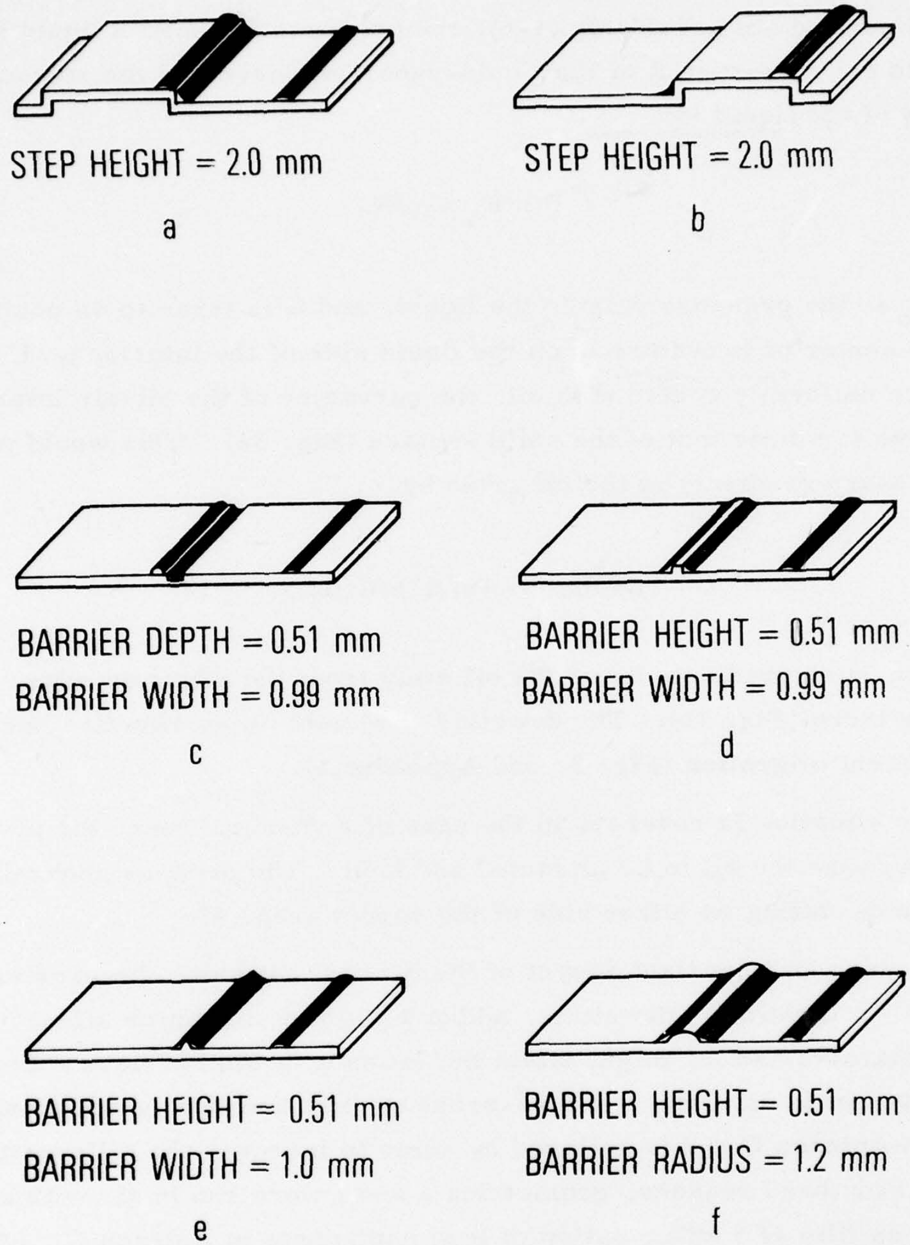


Figure 2. Results of Thermally Induced Oil Migration in the Presence of Various Geometrical Barriers (smooth surface finish)

As pointed out previously (1-6), the pressure P inside a liquid is related to the curvature R of the liquid-vapor interface and the surface tension γ of the liquid by

$$P = P_o + \gamma/R, \qquad [1]$$

where P_o is the pressure outside the liquid, and R is taken to be positive when the center of curvature is on the liquid side of the interface. If an edge were uniformly coated with oil, the curvature of the oil-air interface would have to mimic that of the solid surface (Fig. 3a). This would produce pressure gradients in the oil given by

$$dP/dx = -(\gamma/R^2)dR/dx. \qquad [2]$$

These pressure gradients drive the oil away from the edge and cause dewetting there (Fig. 3b). The dewetted edge acts as an effective barrier to subsequent migration (Fig. 3c and Appendix A).

The situation is reversed in the case of a corner, where the pressure gradients cause the oil to be attracted and held. The process generally results in dewetting on either side of the corner (Fig. 4).

Because an important aspect of the process by which the barriers prevent oil migration is dewetting, additives in the oil, which affect its wetting characteristics, might affect the efficacy of the barriers. Lead napthanate, in particular, is a high-pressure additive that is commonly used with Apiezon C and is believed by some to increase the oil's wetting ability. For these reasons, geometries a and f were run in air with a swabbed-on film of 5 wt% solution of lead napthanate in Apiezon C. (As usual, this was added to heptane to make a 40 vol% solution for swabbing purposes.) The oil migration, however, was still stopped at the barrier.

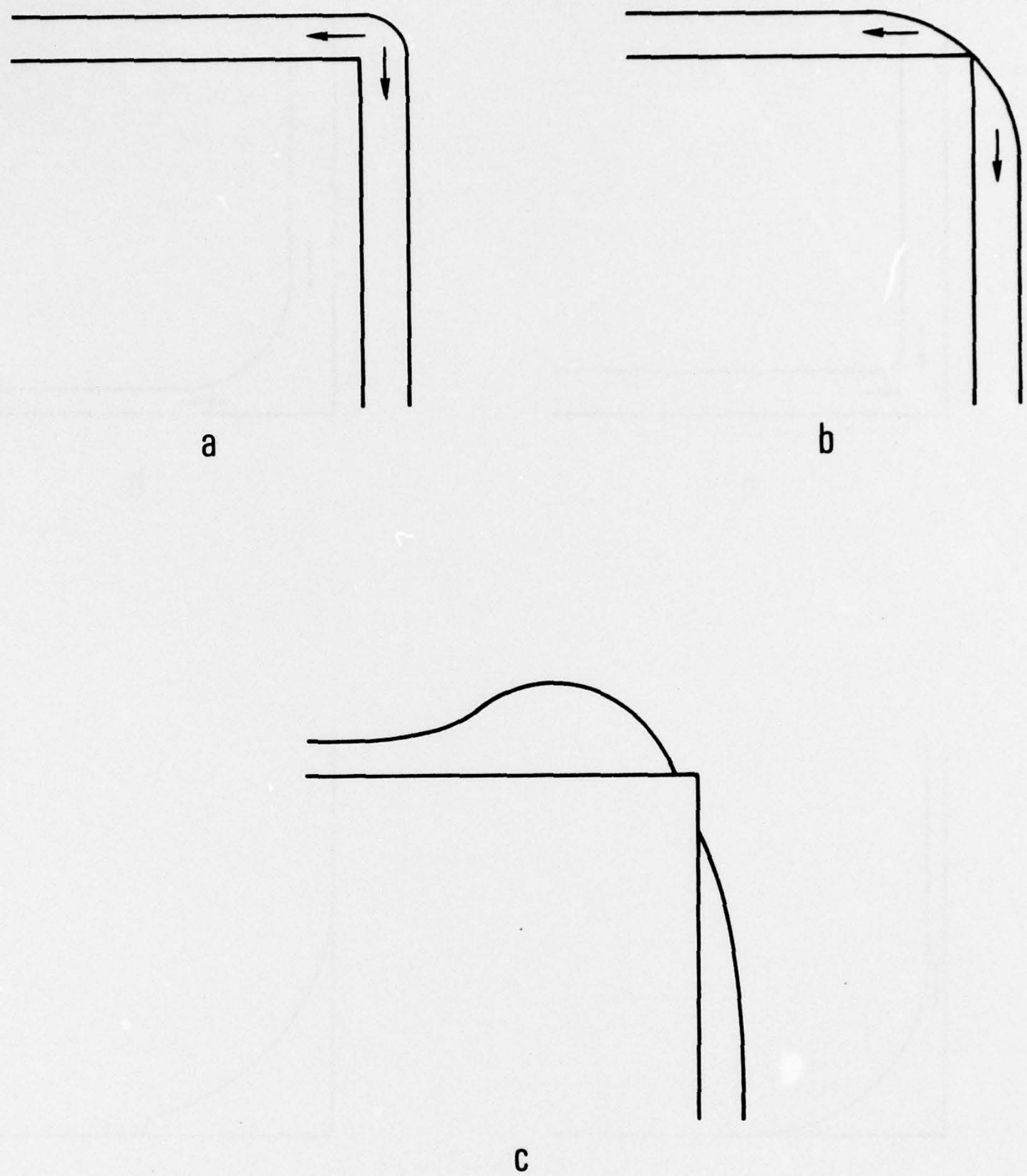


Figure 3. Dewetting of an Edge by Capillary Flow

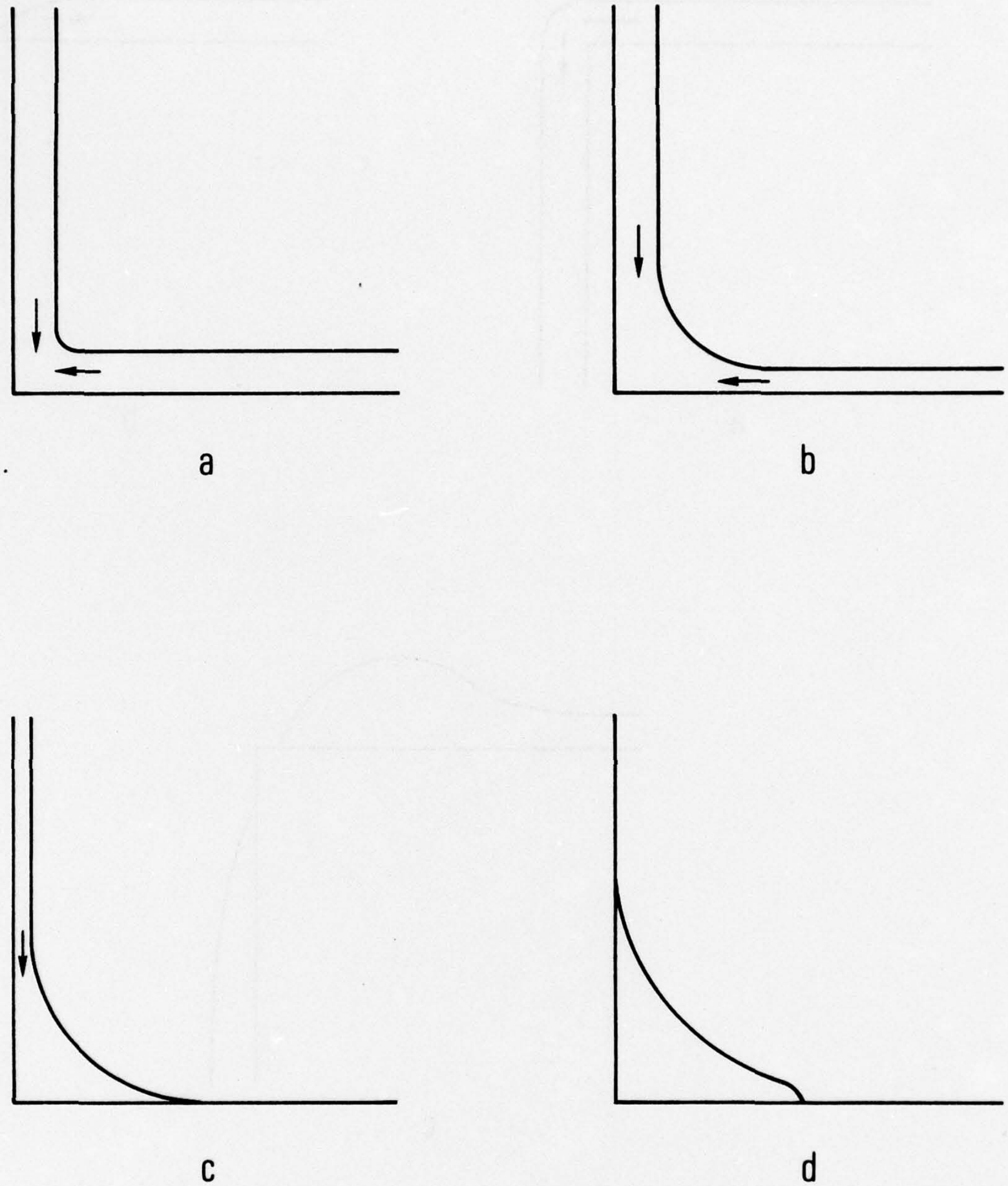


Figure 4. Accumulation of Oil in a Corner

b. Gravitational and Centrifugal Forces, Thick Films

The effectiveness of a geometrical barrier against oil migration depends on the quantity of oil involved. It is expected that when the film thickness exceeds a critical value, flow over a given barrier would occur. This critical thickness for thermally induced oil migration cannot be determined through earth-based experiments. On earth, gravity prevents thick oil films from migrating under the influence of a temperature gradient (Appendix B).

It is possible to drive thick oil films by centrifugal or gravitational forces, which can be used to simulate thermally induced oil migration of thick films as well as to provide data on migration under these conditions. Centrifugal forces would be important in certain high-speed reaction wheels, whereas gravitational forces would be important under the conditions of preflight storage.

Geometrical barriers a, d, e, and f of Fig. 2 were tested under the conditions of gravitational flow. The substrates were held at 50 deg to horizontal such that the oil flowed toward the right. A micro-pipette was used to add small quantities of oil to the left side until the oil was observed to overcome the barriers. The results were basically the same for all four geometries. The oil crossed the barriers when its total quantity exceeded approximately 22 μl over a barrier length of 1 cm.

2. ROUGH SURFACE FINISH

a. Effect on Barriers

The efficacy of the geometrical barriers is greatly diminished when the substrate has a rough surface finish. Results for four of the geometrical barrier samples that were sandblasted are shown in Figs. 5 and 6. The samples were first swabbed with oil in a small circular region near one end. The oil spread out in all directions and easily surmounted all four barriers. The capillary forces involved in oil migration on rough surfaces are strong enough to overcome both gravitational effects and the curvature at the edges.

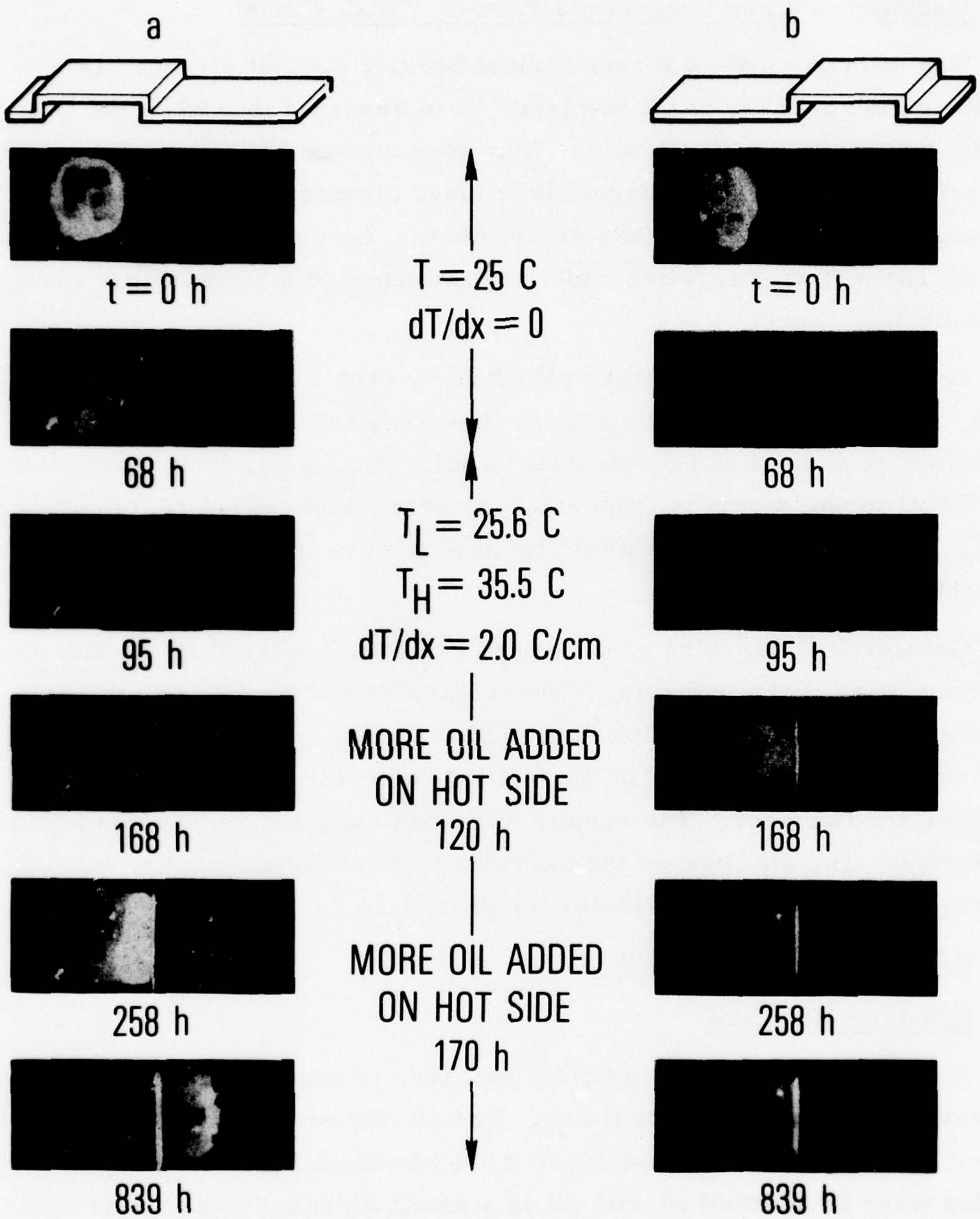


Figure 5. Migration Over Rough-Finished Barriers a and b

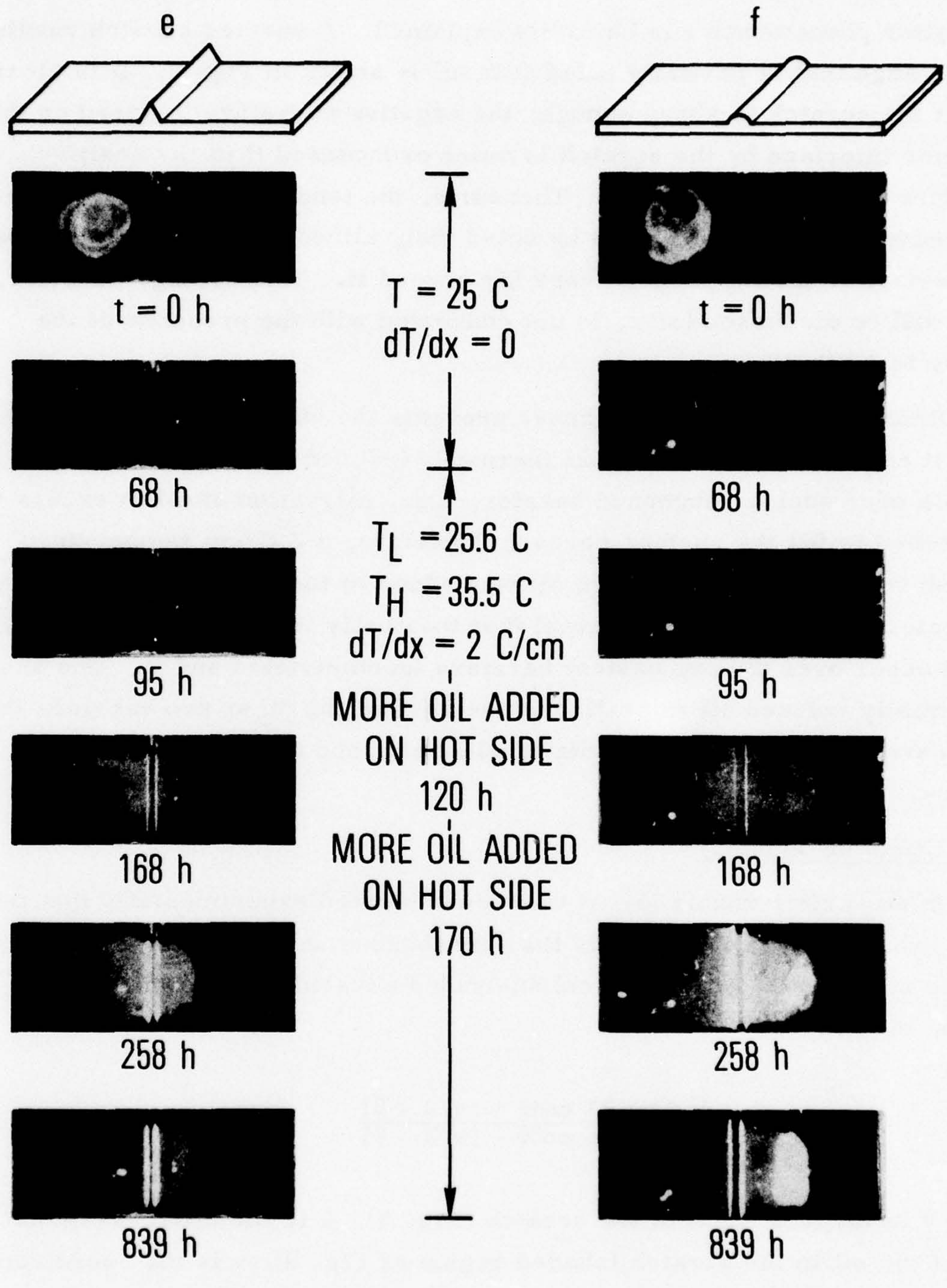


Figure 6. Migration Over Rough-Finished Barriers e and f

This latter phenomenon can be easily explained. A surface scratch running over an edge that is partially filled with oil is shown in Fig. 7. It is clear that, if the scratch is sharp enough, the negative curvature imposed on the oil-vapor interface by the scratch is more pronounced than the positive curvature imposed by the edge. Therefore, the tendency for the oil to dewet at the edge is absent. It should be noted that, although the oil spread over the barrier, it did not proceed very far beyond it. This strange behavior, which will be discussed later, is not connected with the presence of the geometrical barrier.

Because the surface roughness prevents the oil from dewetting at the edge, it appeared reasonable that thermally induced oil migration might be possible over such a roughened barrier, i.e., migration of oil in excess of that needed to fill the surface pores. Therefore, a 2 C/cm temperature gradient was imposed, and more oil was added to the hot (left) sides of the substrates. Figures 5 and 6 reveal that thermally induced oil migration did indeed occur over the two easiest barriers (geometries a and f). The absence of thermally induced oil migration in the case of the other two barriers (b and e) appears to be related to gravitational effects and the holding power of corners.

b. Effect on Velocity

In an earlier report (5), it was demonstrated experimentally that thermally induced migration of oil is less pronounced on substrates with high surface roughness. Mathematical analysis indicated that the migration should, in fact, cease when

$$\frac{1}{A}\frac{dA}{dx} = \frac{2\tau}{\gamma}\,\frac{\cot\theta + (\pi/2 - \theta)}{\cot\theta - (\pi/2 - \theta)}$$

where θ is the half angle of the scratch (Fig. 8), A is the cross-sectional area of the oil in the scratch (shaded region of Fig. 8), x is the coordinate along the scratch, and the other parameters are as defined earlier.

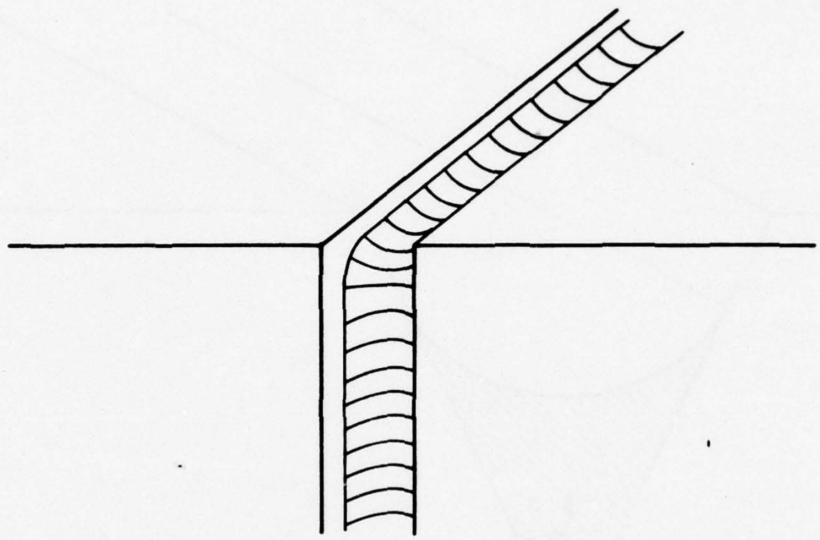


Figure 7. Migration of Liquid in a Scratch Around an Edge

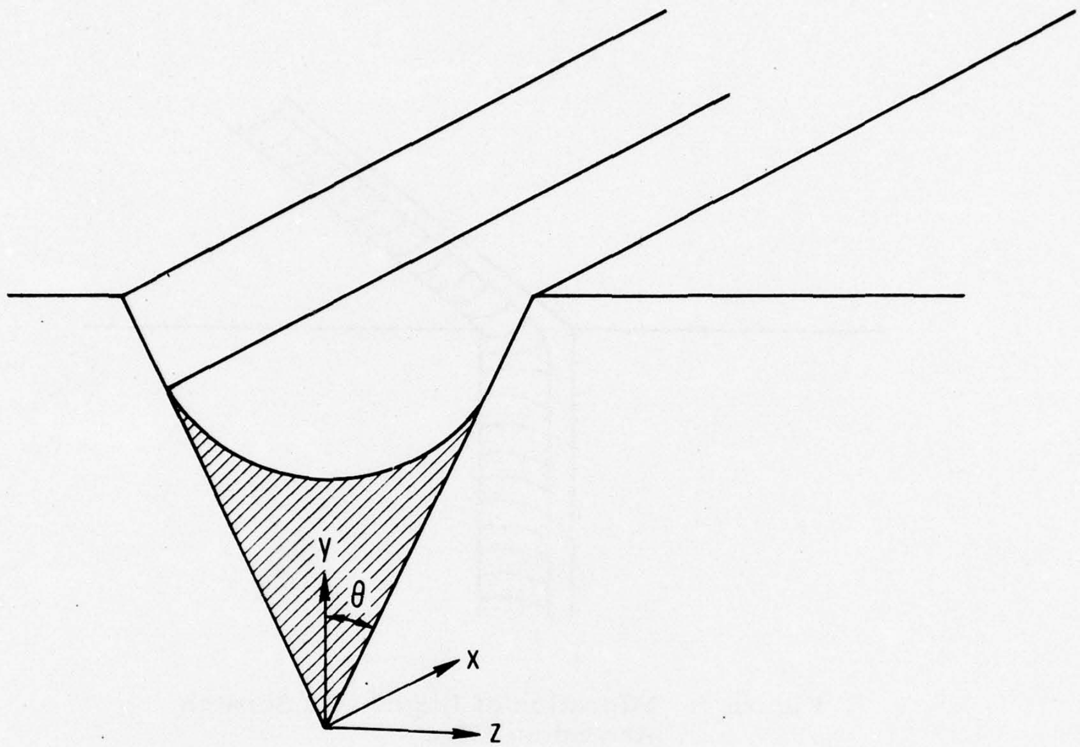


Figure 8. Oil Contained in a Surface Scratch

We now demonstrate that the velocity of thermally induced oil migration is also affected by surface roughness. In Appendix C, an expression for this velocity is derived:

$$\overline{V} = \frac{h\tau}{2\eta} g(\theta) \quad , \qquad [3]$$

where

$$g(\theta) = (128\theta^2/\pi^4) \sum_{n\ \mathrm{odd}} [n^3(n + 4\theta/\pi)]^{-1} \quad .$$

Our earlier derivation for smooth surfaces (3) corresponds to Eq. [3] with $g(\theta) = 1$. For a smooth surface (θ = 90 deg), the above expression yields instead g(90 deg) = 1.11. This 11% error is due to the approximate geometry used in the derivation (Fig. C-1). Nevertheless, the tabulated values of $g(\theta)$ given in Table 1 show that the velocity of flow should be smaller for rough surfaces.

This prediction appears to be confirmed by the results of Fig. 9. A substrate was sanded with 60-grit sandpaper with the scratches running along the longer dimension. The substrate was then dip-coated and subjected to a temperature gradient of 2 C/cm. Comparison with earlier results for smooth surfaces, e.g., Fig. 3 of Ref. (3), indicates a slower velocity of migration.

B. CHEMICAL BARRIERS

1. ANTICREEP AGENTS

Nyebar F was used routinely in our experiments to contain the oil on the substrates. This material prevents both thermally induced and capillary-driven oil migration on smooth and rough surfaces. It was desired to determine the relative efficacy of Nyebar F as a creep barrier in comparison with the geometrical barriers. Toward this end, the gravitational flow experiments described earlier (sample tilted 50 deg to horizontal) were performed

Table 1

$g(\theta)$ vs θ

θ, deg	g(θ), deg
5	0.009
10	0.033
15	0.069
20	0.113
25	0.164
30	0.220
35	0.282
40	0.346
45	0.414
50	0.485
55	0.558
60	0.632
65	0.709
70	0.787
75	0.866
80	0.946
85	1.028
90	1.110

on a smooth, flat surface with a band of Nyebar F across the center. We discovered that, in this configuration, the Nyebar F and the geometrical barriers are about equal in their ability to restrain oil flow. Both barriers were able to contain approximately 22 μl over a 1 cm length before flow occurred. This result supports our theory that the geometrical barriers function primarily by producing a dewetted area because it is this mechanism by which the chemical agent inhibits migration.

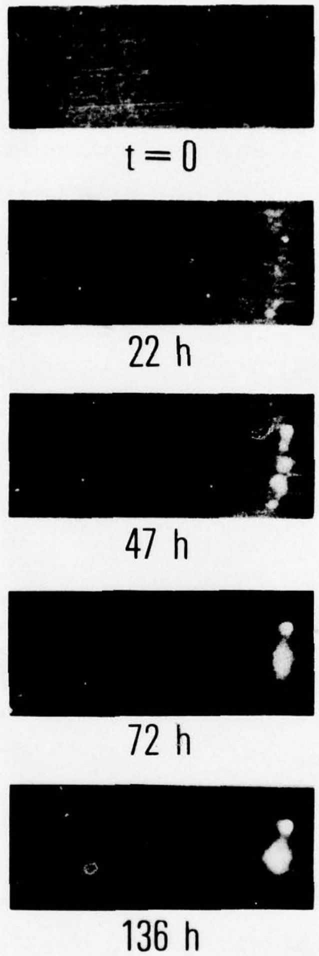


Figure 9. Thermally Induced Oil Migration or a Rough Surface

2. DRY SURFACES

Oil films cannot be driven onto a dry region of a metal surface by surface tension gradients alone because this type of flow results when oil with low surface tension is pulled by oil with a higher surface tension. If there is no oil present to do the pulling, no flow is possible.

For this reason, if the metal surface is such that an oil film is not stable on it whereby the film breaks up into disjointed drops, thermally induced oil migration will not occur. This is demonstrated in Fig. 10. The substrates in this case were not adequately cleaned; they were only wiped with a heptane-soaked swab. For the sample on the left, the film beaded up completely, and thermally induced migration was entirely blocked. For the other sample, the beading was not as complete, and oil migration still occurred, although it was significantly hampered. Thus, surface preparation plays an important role in the occurrence of oil migration.

3. SELECTIVE MIGRATION

In an earlier section, it was pointed out that the oil migration observed in Figs. 5 and 6 stopped a short distance beyond the geometrical barriers. It was originally expected that the oil would spread evenly over the entire surface under the influence of capillary forces. That the failure of the oil to continue spreading cannot be attributed to insufficient oil is obvious from the last picture in the sequence for geometry f.

A clue to this strange behavior is the fact that the dark regions in the pictures are not entirely devoid of oil. Visual observation of the substrates reveals a discolored band in advance of the stalled film front. From past experience, we know that such a discolored region is due to the presence of an oil film that is too thin to be readily observed by our fluoresence technique. This band of fluid in advance of the main body of oil has anomalous properties. A drop of oil placed on this region will not spread. Instead, it remains as a bead. This is in contradiction to the way oil drops spread rapidly when placed on both wet and dry substrates with this surface roughness. On the completely dry region beyond the anomalous band, the spreading

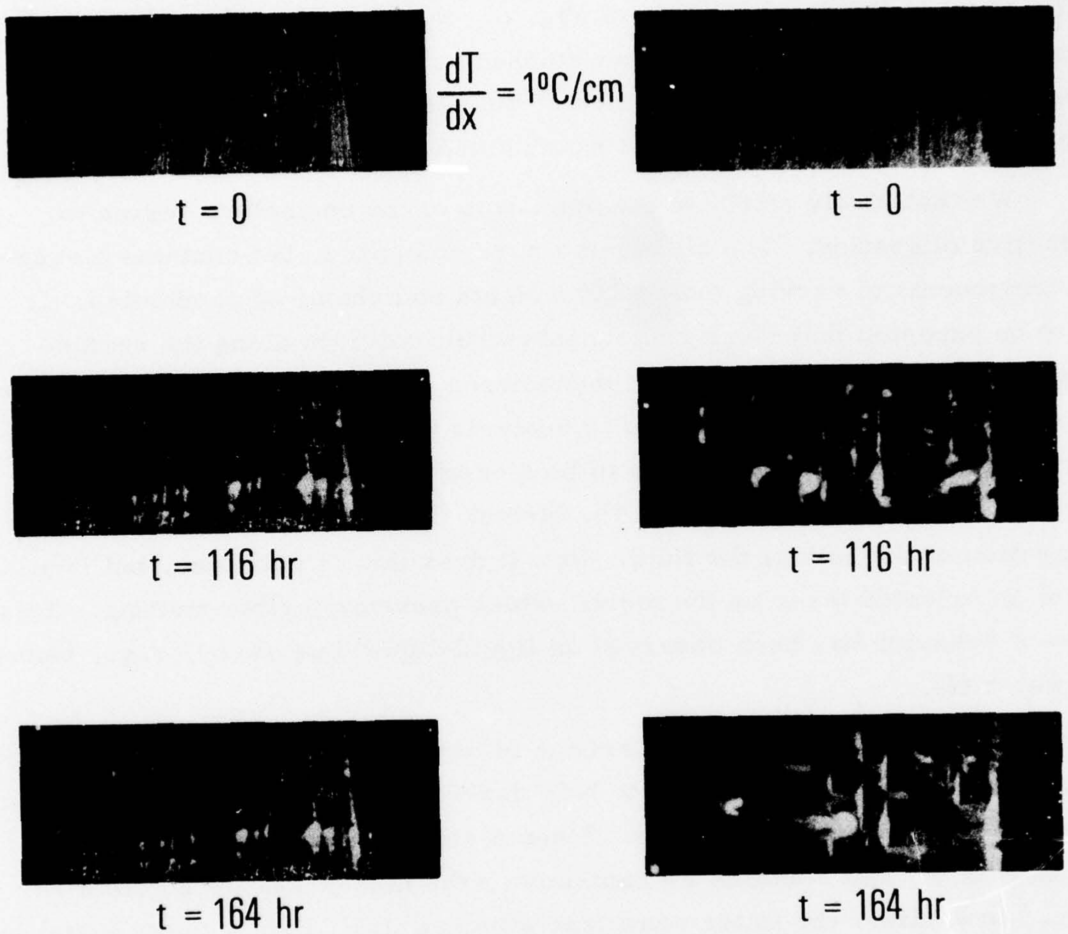


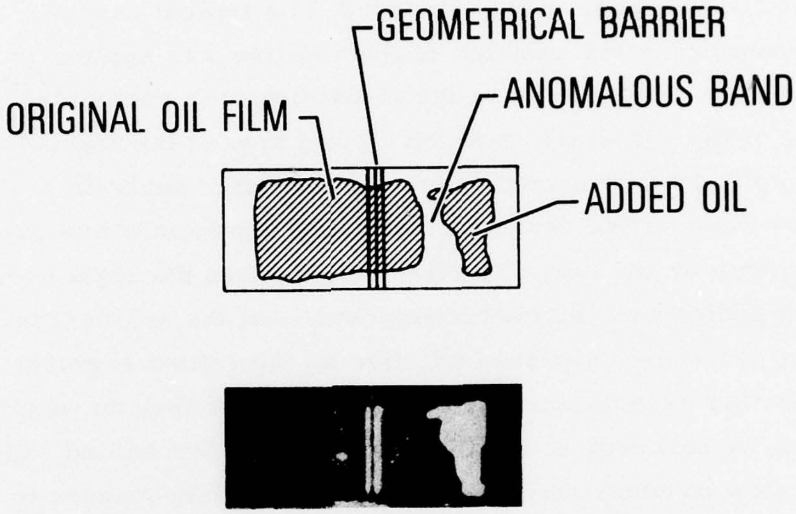
Figure 10. Effect of Surface Preparation on Thermally Induced Oil Migration

occurs as usual. In Fig. 11 for example, a substantial quantity of oil has been added to the dry region in front of the anomalous band on the substrate subsequent to the developments of Fig. 6. Note how the oil spread evenly over the previously dry region but stopped at the anomalous region. This effect is not caused by the presence of the geometrical barrier. Exactly the same behavior occurs on flat sandblasted substrates.

We tentatively attribute the formation of the anomalous region to selective migration. The oil is not a pure compound, but contains a range of components of varying molecular weights and chemical properties. It is to be expected that these components would migrate along the surface grooves at different rates. The phenomenon of preferential migration is well known to chemists and is applied in analysis by the paper chromatography technique. Here, there appears to be a case of metal chromatography in which the component that moves the fastest also acts as an inhibitor to the migration of the bulk of the fluid. How it does this is not clear, but it may form an oriented layer on the metal, which prevents further wetting. This type of behavior has been observed on liquid-liquid interfaces, e.g., benzene on water (7).

We also observed the occurrence of metal chromatography in a slightly different experiment. In order to help describe this experiment, some background information is necessary. When a steel substrate is exposed to a solution of oil that contains Pb napthanate, the high-pressure additive referred to earlier, the latter compound attaches itself firmly to the metal in the form of a coating one to two monolayers thick. The oil can be readily removed from the substrate by washing with heptane without removing the additive. The additive can then be detected by means of electron spectroscopy for chemical analysis (ESCA), an analytical tool for determining the composition of thin surface layers.[1] Our objective was to determine whether or not the additive migrated along with the oil on metal substrates. For

[1] Phillips, R. W., and Tolentino, L. U., to be published.



GEOMETRY e
(triangular barrier)

this, a special substrate was prepared (Fig. 12). The top surface was sandblasted to facilitate spreading of the oil by way of capillary flow. The bottom surface was undercut such that, after spreading of the oil, the substrate could be broken into sections and each section separately washed and analyzed to determine the presence of the additive. In a typical experiment, a quantity of oil that contained 5 wt% solution of the additive was applied to the center segment and allowed to spread to the remaining four segments.[2] Due to a slight tilting of the substrate, bulk oil flowed toward the right (lower) side while only capillary flow occurred toward the left. Analysis of the separate segments for the additive revealed that no Pb napthanate was present on the two segments on the left. The first segment on the right carried about half as much additive as the center segment, and the segment on the extreme right carried the same amount of additive as the center segment. From this and other similar experiments, it can be concluded that the additive is carried along by bulk flow of the oil, but that it is left behind under conditions of capillary flow on steel surfaces. The latter result appears to be due to a chromatographic effect.

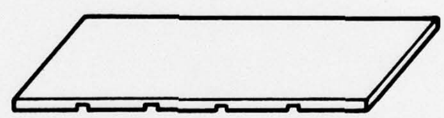


Figure 12. Substrate Used in the Additive Migration Experiments

[2] This experiment was conceived by R. W. Phillips. The ESCA analysis was performed by L. U. Tolentino.

IV. SUMMARY

The three mechanisms for the surface transport of oil, capillary flow, surface tension gradient flow, and external forces are discussed below.

A. CAPILLARY FLOW

Capillary flow describes the tendency of oil to flow along surface scratches and corners. The flow is driven by pressure gradients in the oil caused by variations in the radius of curvature of the oil-vapor interface. It does not occur on flat, polished surfaces. On rough surfaces, it can be prevented by the application of an anticreep agent.

B. SURFACE TENSION GRADIENT FLOW

Surface tension gradients can be produced in two ways: by temperature gradients (3) or by concentration gradients (8). In either case, the oil with the lower surface tension is pulled by that with the higher surface tension. This type flow can be stopped in three ways:

1. Dewetting. Unless the oil is in contact with oil that has a higher surface tension, there is nothing to pull it; therefore no migration can occur.
2. Capillary forces. The flow can be prevented if capillary forces are present that are sufficiently strong to fix the oil in place. This occurs, for example, on very rough surfaces (5) and in the vicinity of corners.
3. External forces. The flow can be prevented if stronger external forces are present that oppose it. For example, gravitational forces become significant when the film thickness becomes too great.

C. EXTERNAL FORCES

During storage on earth, gravitational forces cause the flow of oil films of sufficient thickness. Although there are negligible gravitational forces in space, there can be appreciable centrifugal forces for high-speed reaction wheels. Flow induced by external forces can be prevented by chemical and geometrical barriers if the force or the quantity of oil involved is not too great.

APPENDIX A. DEWETTING AT EDGES

Here, we demonstrate that the dewetting forces at an edge are much stronger than the driving force due to a temperature gradient.

First, recall the expression for the average velocity of flow $\overline{V}$ of an oil film of thickness h under the influence of a temperature gradient dT/dx and a pressure gradient dP/dx (5)

$$\overline{V} = \frac{h}{2\eta}\left(\tau - \frac{2}{3}\frac{dP}{dx}h\right) ,$$

where η is the viscosity, $\tau = d\gamma/dT\ dT/dx$, and γ is the surface tension. Thermally induced oil migration will only occur if $|\tau|$ is greater than $\left|\frac{2}{3}\frac{dP}{dx}h\right|$.

The derivative of Eq. [1] in the presence of a temperature gradient is

$$dP/dx = \tau/R - (\gamma/R^2)dR/dx \qquad .$$

We select the following typical values for the parameters in the above equations: $\tau = 0.2$ dyne/cm^2 (Apiezon C with dT/dx = 2 C/cm), $\gamma = 32$ dyne/cm^2, $R = 10^{-2}$ cm, dR/dx = 1.0, and $h = 10^{-4}$ cm. This yields

$$\frac{2}{3}\frac{dP}{dx}h = 21.3 \text{ dyne/cm}^2 \qquad ,$$

which is two orders of magnitude larger than τ.

APPENDIX B. THERMAL MIGRATION AND THICK FILMS

Oil films that are sufficiently thick will not migrate under the influence of a temperature gradient in the earth's gravitational field. To prove this statement, we recall the expression for the velocity of flow in x direction V_x of an oil film in a temperature gradient dT/dx (5)

$$V_x = (h/2\eta)(\tau \cos\theta - (2h/3)dP/dx) \quad , \qquad [B-1]$$

where h is the film thickness, η is viscosity, $\tau = d\gamma/dT \; dT/dx$, γ is surface tension, $\theta = \tan^{-1}(dh/dx)$, and P is pressure given by

$$P = P_o + \gamma/R + \rho g(h - y) \quad , \qquad [B-2]$$

where P_o is the pressure above the liquid surface, ρ is the density, R is the curvature of the oil-vapor interface, and y is the distance measured from the solid-liquid interface. The condition under which oil flow ceases $V_x = 0$ is determined from Eq. [B-1] as

$$h\,dP/dx = (3\tau \cos\theta)/2 \quad . \qquad [B-3]$$

The maximum effect occurs when the curvature effects are absent. Leaving off the term R in Eq. [B-2] gives

$$dP/dx = \rho g \; dh/dx = \rho g \tan\theta \quad . \qquad [B-4]$$

Combining Eqs. [B-3] and [B-4] and solving for $\tan\theta$ gives the maximum slope as

$$(dh/dx)^2 = \tan^2\theta = \frac{1}{2}\left[\sqrt{1 + (3\tau/\rho g h)^2} - 1\right] \quad , \qquad [B-5]$$

which indicates that the maximum possible slope decreases with increasing film thickness in a gravitational field. For example, if a 500 μm film of Apiezon C is subjected to a temperature gradient of 2 C/cm, Eq. [B-5] predicts that $(dh/dx)/h = 0.1/cm$. That is, the film thickness could not vary by more than 10%/cm, and no substantial migration would be observed. Our experiments have verified that the thicker films do not, in fact, migrate in the earth's gravitational field.

APPENDIX C. VELOCITY OF FLOW IN A SURFACE SCRATCH

Under the conditions of creeping motion, the Navier-Stokes equations can be approximated by the Stokes equations (9)

$$\nabla^2 \vec{V} = \frac{1}{\eta} \nabla P \quad . \qquad [C-1]$$

The continuity equation

$$\nabla \cdot V = 0$$

together with the approximation $V_y = V_z = 0$ (Fig. 8) gives $dV_x/dx = 0$. Thus, Eq. [C-1] becomes

$$\frac{\partial^2 V_x}{\partial y^2} + \frac{\partial^2 V_x}{\partial z^2} = \frac{1}{\eta} \frac{\partial P}{\partial x} \quad .$$

If we concern ourselves only with determining the velocity of flow when the scratch is uniformly filled with oil, then we can set $\partial P/\partial x = 0$ because the pressure gradient term arises only when the degree of filling varies along the length of the scratch. To further simplify the problem, it is best to adopt the geometry shown in Fig. C-1 and to make use of cylindrical coordinates. In this way, the problem reduces to solving the differential equation

$$\frac{1}{r} \frac{d}{dr}\left(r \frac{dV}{dr}\right) + \frac{1}{r^2} \frac{d^2 V}{d^2 \phi} = 0 \quad , \qquad [C-2]$$

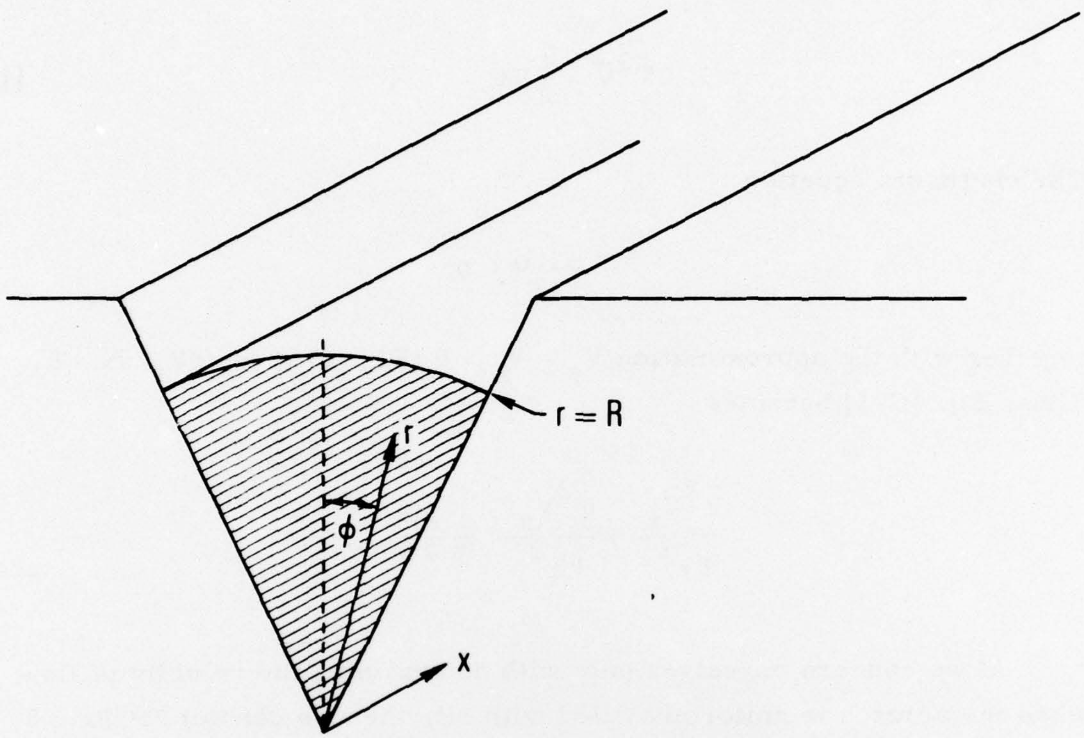


Figure C-1. Geometry used to Calculate Flow Velocity of Oil in a Surface Scratch

with the boundary conditions

$$V = 0 \qquad \text{at } \phi = \pm\theta \quad ,$$
$$dV/dr = \tau/\eta \text{ at } r = R \quad . \qquad [C\text{-}3]$$

By using the standard techniques for solving second-order partial differential equations, we obtain the general solution to Eq. [C-2] as

$$V = \sum_{\alpha} A_{\alpha} (\cos \alpha\phi + B_{\alpha} \sin \alpha\phi)\left(r^{\alpha} + C_{\alpha} r^{-d}\right) \quad .$$

The symmetry condition $V(r, \phi) = V(r, -\phi)$ gives $B_{\alpha} = 0$. The condition $V(0, \phi) = 0$ gives $C_{\alpha} = 0$. The two boundary conditions [C-3] can be met by requiring that

$$dV/dr\Big|_{r = R} = \frac{d}{dr} \sum_{\alpha} A_{\alpha} r^{\alpha} \cos \alpha\phi \Big|_{r = R}$$

$$= \sum_{\alpha} \alpha A_{\alpha} R^{\alpha - 1} \cos \alpha\phi = F(\phi) \quad ,$$

where $F(\phi)$ is defined by Fig. C-2. Fourier analysis then yields the coefficients A_{α}, and gives as the solution for the velocity

$$V = \frac{8\theta\tau R}{\pi^2\eta} \sum_{n} \frac{(-1)^n}{(2n + 1)^2} (r/R)\ (2n + 1)\pi/2\theta \cos \frac{(2n + 1)\pi}{2\theta} \phi \quad .$$

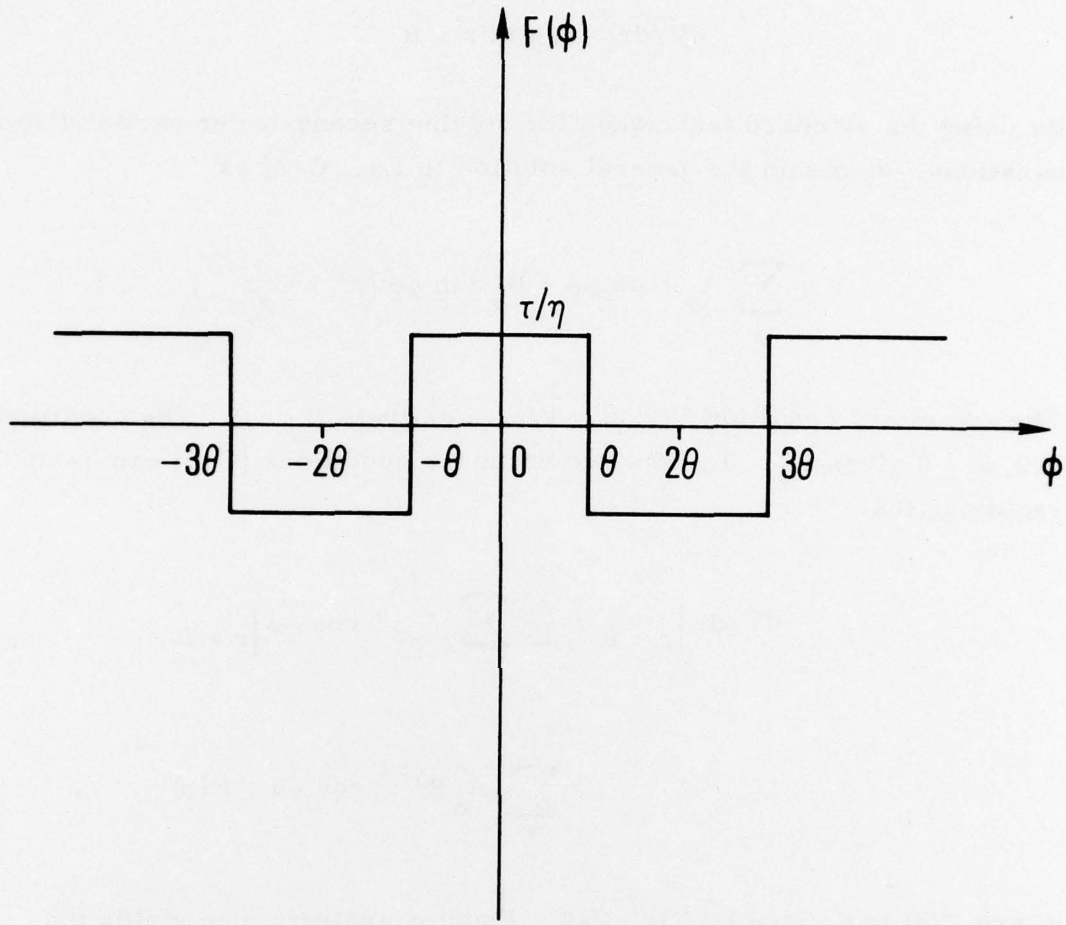


Figure C-2. Definition of the Function $F(\phi)$

The average velocity is given by

$$\overline{V} = \frac{2}{\theta R^2} \int_o^\theta \int_o^R V(r, \phi) r dr d\phi \quad ,$$

which results in

$$\overline{V} = \frac{R\tau}{2\eta} g(\theta) \quad , \qquad [C-4]$$

where

$$g(\theta) = 2(8\theta/\pi^2)^2 \sum_{n\,odd} \left[n^3(n + 4\theta/\pi)\right]^{-1} \quad .$$

Replacement of R by h in Eq. [C-4] then yields Eq. [3]

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